US009339752B2

(12) **United States Patent**
Reddy et al.

(10) **Patent No.: US 9,339,752 B2**
(45) **Date of Patent: May 17, 2016**

(54) **CONFIGURATIONS AND METHODS OF CO_2 CAPTURE FROM FLUE GAS BY CRYOGENIC DESUBLIMATION**

(71) Applicant: **FLUOR TECHNOLOGIES CORPORATION**, Aliso Viejo, CA (US)

(72) Inventors: **Satish Reddy**, Laguna Beach, CA (US); **Joseph Yonkoski**, Irvine, CA (US); **Paul Mathias**, Aliso Viejo, CA (US)

(73) Assignee: **Fluor Technologies Corporation**, Sugar Land, TX (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 335 days.

(21) Appl. No.: **13/940,019**

(22) Filed: **Jul. 11, 2013**

(65) **Prior Publication Data**

US 2014/0090415 A1 Apr. 3, 2014

Related U.S. Application Data

(60) Provisional application No. 61/670,427, filed on Jul. 11, 2012.

(51) **Int. Cl.**

F25J 3/00	(2006.01)
F25J 1/00	(2006.01)
B01D 53/00	(2006.01)
B01D 7/02	(2006.01)
F25J 3/06	(2006.01)
B01D 7/00	(2006.01)

(52) **U.S. Cl.**

CPC ***B01D 53/002*** (2013.01); ***B01D 7/00*** (2013.01); ***B01D 7/02*** (2013.01); ***F25J 3/067*** (2013.01); *B01D 2257/504* (2013.01); *B01D 2258/0283* (2013.01); *F25J 2205/20* (2013.01); *F25J 2210/70* (2013.01); *Y02C 10/12* (2013.01); *Y02P 70/34* (2015.11)

(58) **Field of Classification Search**

CPC B01D 53/002; B01D 7/00; B01D 7/02; B01D 2258/0283; B01D 2257/054; Y02C 10/12; F25J 3/067; F25J 2205/20; F25J 2210/70

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2,579,421 A * 12/1951 Egan C10G 31/06 62/335
2,738,658 A * 3/1956 Brouson C01B 31/22 62/604

(Continued)

FOREIGN PATENT DOCUMENTS

DE 60204540 3/2006
FR 2867092 9/2005

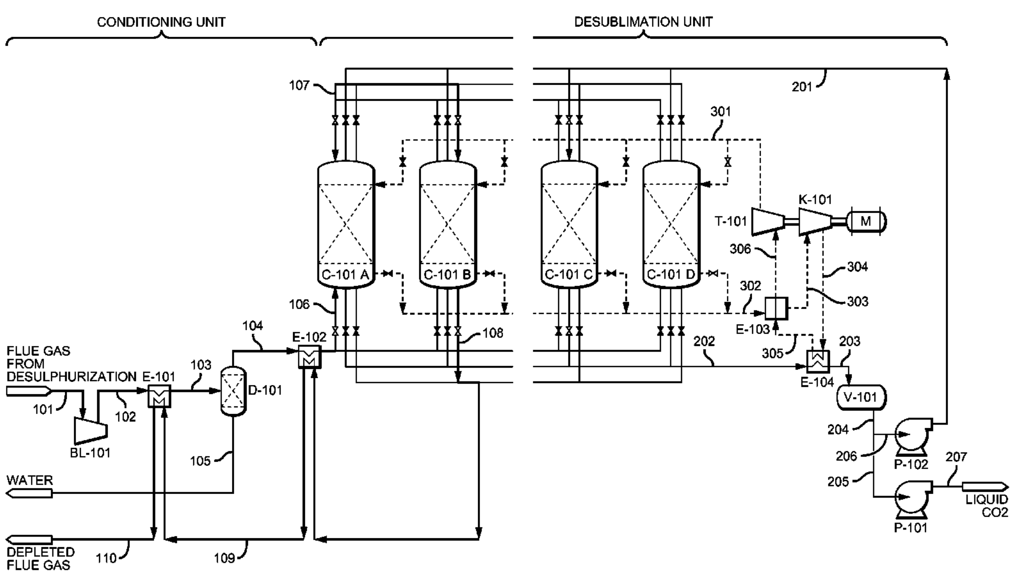
(Continued)

Primary Examiner — Frantz Jules
Assistant Examiner — Keith Raymond
(74) *Attorney, Agent, or Firm* — Conley Rose, P.C.; Kristin Jordan Harkins

(57) **ABSTRACT**

Systems and methods of CO_2 desublimation are presented in which refrigeration content is retained within the system. Most preferably, refrigeration content is recycled by providing the refrigeration content of a CO_2-lean feed gas to the CO_2-containing feed gas and to pre-cooling of a desublimator, and/or by providing refrigeration of effluent of a desublimator in regeneration to a refrigerant in a closed refrigeration cycle for deep-cooling of another desublimator.

9 Claims, 4 Drawing Sheets



(56) **References Cited**

U.S. PATENT DOCUMENTS

4,265,088	A	5/1981	Funk	
4,378,984	A	4/1983	Cheng	
2004/0148961	A1 *	8/2004	Clodic	B01D 53/002 62/532
2008/0302133	A1 *	12/2008	Saysset	B01D 53/002 62/617
2011/0023537	A1 *	2/2011	Assink	B01D 7/02 62/617
2011/0226010	A1	9/2011	Baxter	
2012/0174623	A1 *	7/2012	Clodic	B01D 7/02 62/617

FOREIGN PATENT DOCUMENTS

WO	2009047341	4/2009
WO	2012068588	5/2012
WO	2012174418	12/2012

* cited by examiner

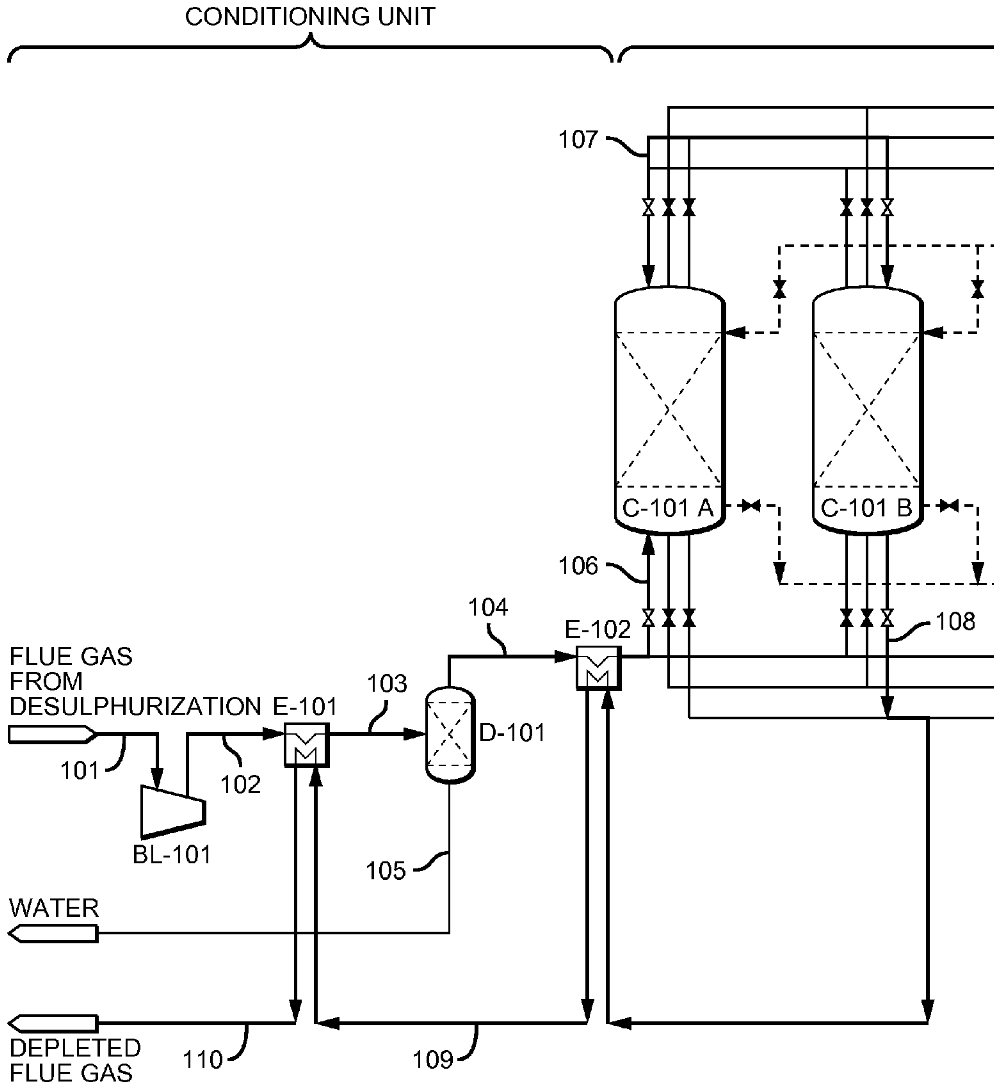
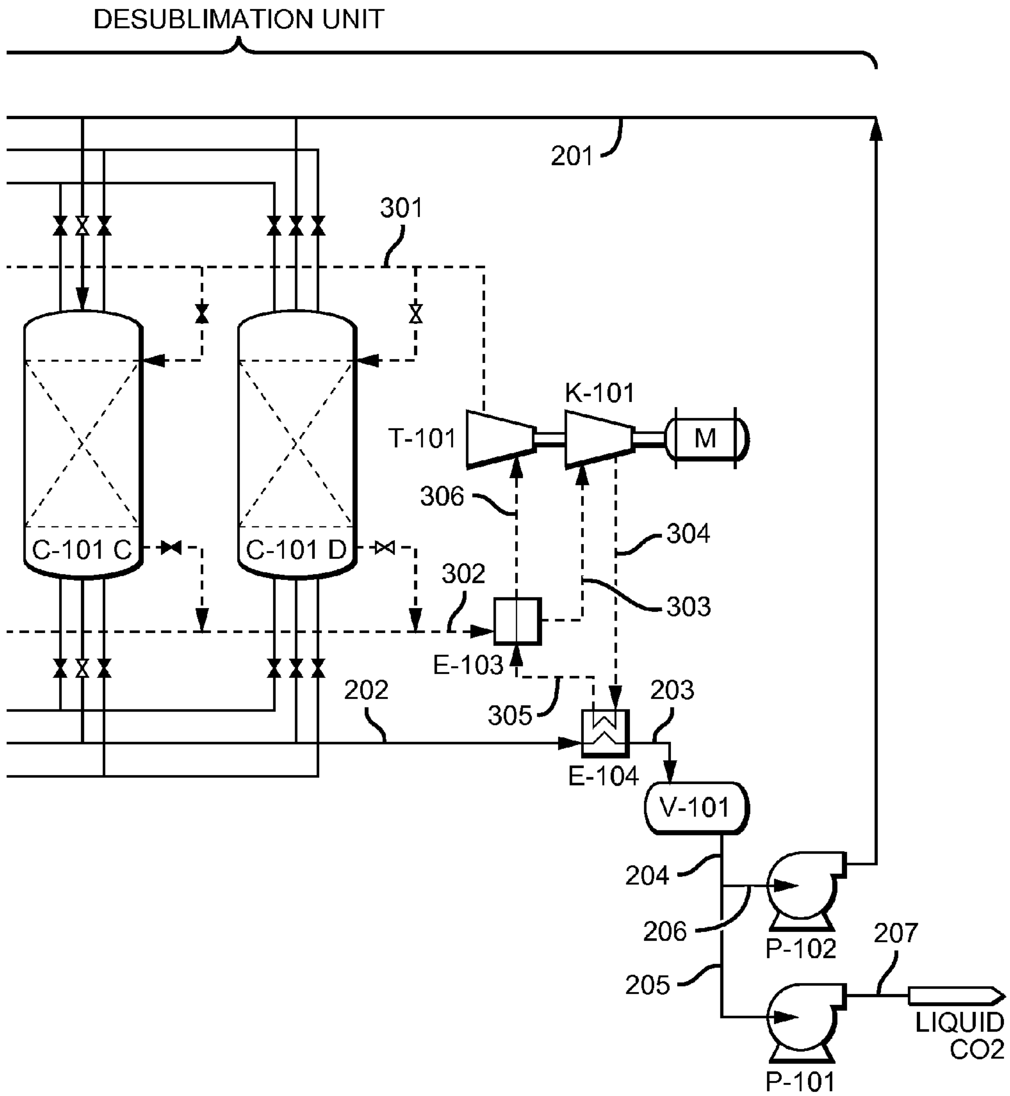

CONDITIONING UNIT
107
C-101 A
C-101 B
106
104
E-102
108
FLUE GAS
FROM
DESULPHURIZATION
E-101
103
D-101
101
102
BL-101
105
WATER
DEPLETED
FLUE GAS
110
109

FIG. 1A



DESUBLIMATION UNIT
201
301
K-101
T-101
M
306
304
C-101 C
C-101 D
302
303
E-103
202
203
305
E-104
V-101
204
206
P-102
207
205
LIQUID
CO2
P-101

FIG. 1B

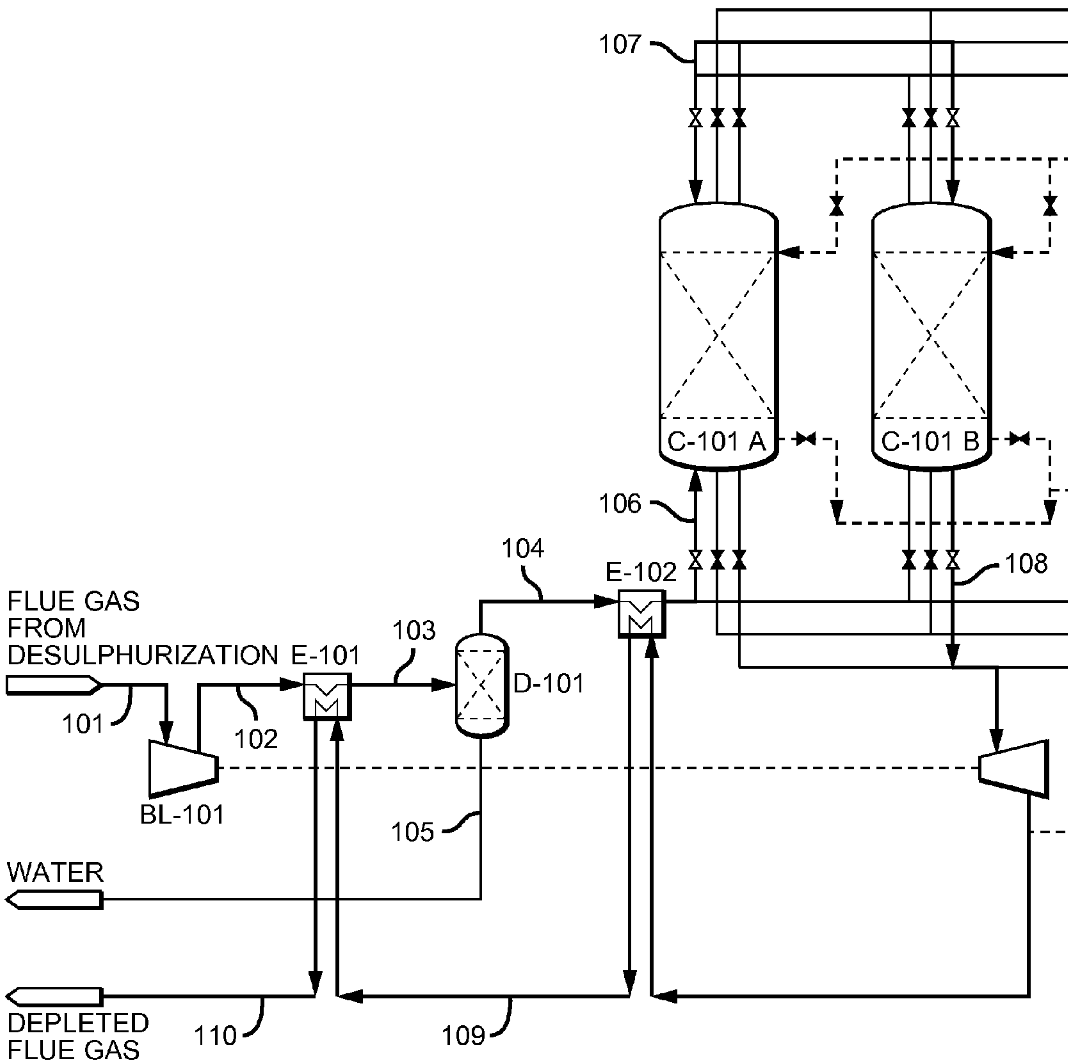

107
C-101 A
C-101 B
106
108
104
E-102
FLUE GAS
FROM
DESULPHURIZATION
E-101
103
D-101
101
102
BL-101
105
WATER
DEPLETED
FLUE GAS
110
109

FIG. 2A

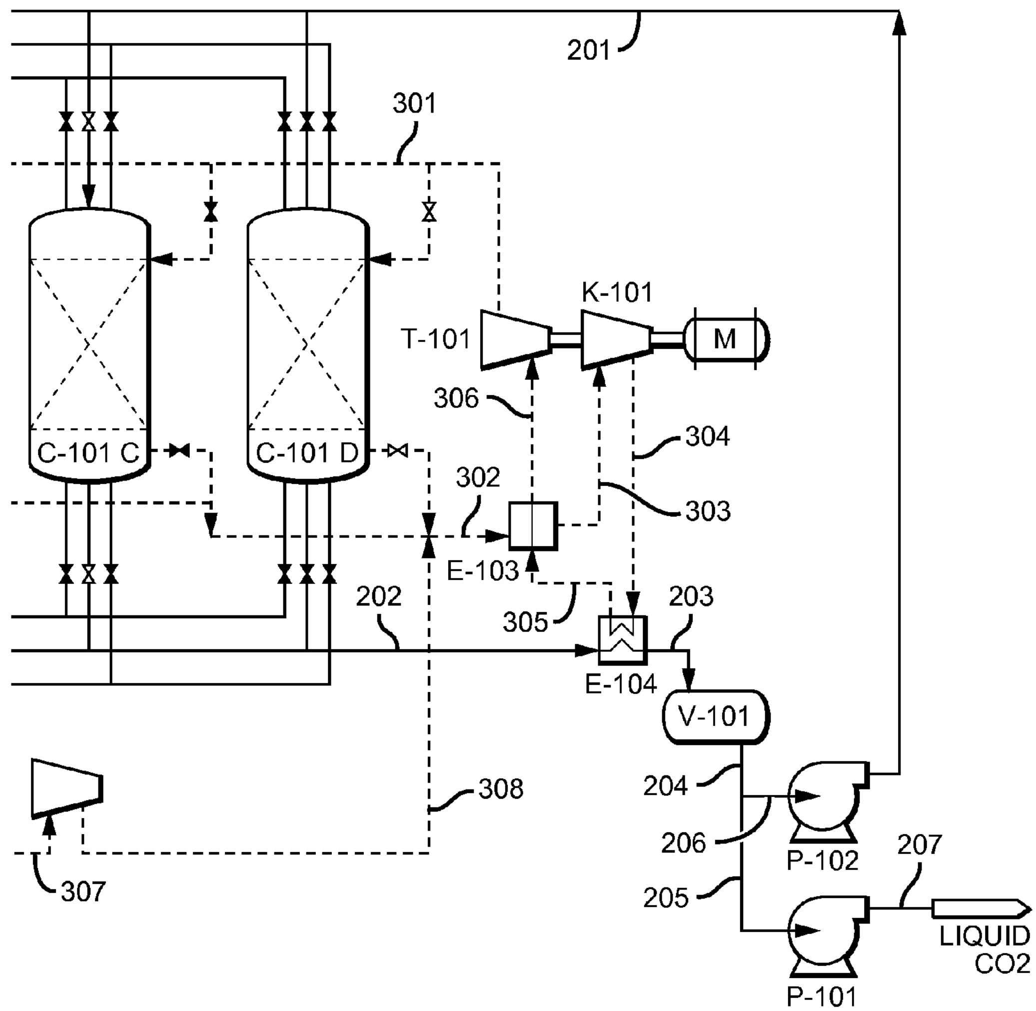

201
301
C-101 C
C-101 D
T-101
K-101
M
306
304
302
303
E-103
305
202
203
E-104
V-101
204
206
205
308
307
P-102
207
P-101
LIQUID
CO2

FIG. 2B

CONFIGURATIONS AND METHODS OF CO_2 CAPTURE FROM FLUE GAS BY CRYOGENIC DESUBLIMATION

This application claims priority to U.S. provisional application with the Ser. No. 61/670,427, which was filed on Jul. 11, 2012, and which is incorporated by reference herein.

FIELD OF THE INVENTION

The field of the invention is systems and methods of CO_2 desublimation from flue gas and recovery thereof.

BACKGROUND OF THE INVENTION

The increasing carbon dioxide concentration in the atmosphere is suggested to be linked to increasing temperatures and changes in the World's climate, and significant interest has been given to CO_2 capture, especially from combustion gases. One well established CO_2 capture method uses a chemical solvent (typically amine based) to absorb CO_2 from flue gas. This method is effective, however presents several difficulties: (1) solvents must be manufactured, purchased, and transported, resulting in significant expenses; (2) most solvents (and especially amine solvents) tend to degrade via oxidative and/or thermal pathways. As a consequence the solvent must be maintained and/or continuously replaced; and (3) some solvents present environmental concerns as they may form harmful compounds once emitted to the atmosphere.

Other known CO_2 capture processes may circumvent at least some of these drawbacks, including PSA (pressure swing adsorption) or membrane processes. However, these processes are often costly because they carry energy penalties caused by the regeneration of CO_2 loaded adsorbents or by the need for recompression of flue gas upstream of a membrane.

CO_2 can also be removed from a gas stream based on the principles of cryogenic removal or desublimation. For example, U.S. Pat. Pub. No. 2011/0226010 teaches separation of CO_2 from flue gas by compression, expansion and refrigeration. While such process is at least conceptually attractive, significant energy requirements often render such separation impracticable. This and all other extrinsic materials discussed herein are incorporated by reference in their entirety. Also, where a definition or use of a term in an incorporated reference is inconsistent or contrary to the definition of that term provided herein, the definition of that term provided herein applies and the definition of that term in the reference does not apply.

In another example, as described in U.S. Pat. No. 4,265,088, CO_2 is frozen out from a gas stream, and so isolated solid CO_2 is then sublimated after it has been deposited in a tower. Such configuration, however, is typically not able to generate a pure CO_2 stream and requires in most cases substantial quantities of energy for CO_2 recovery. Similarly, U.S. Pub. No. 2011/0023537 teaches desublimation of CO_2 on porous media and CO_2 recovery via fluid CO_2 to so produce a warm porous medium. However, use of such porous media may be problematic due to potential clogging. Furthermore, CO_2 recovery using liquid CO_2 as described in the '537 reference is not energy efficient under various circumstances.

Thus, there is still a need for energy efficient systems and methods of capture of CO_2 from a flue gas by cryogenic desublimation, and a further need for the removal of the solid CO_2.

SUMMARY OF THE INVENTION

The present invention is directed to various configurations and methods of CO_2 removal with desublimation in which

refrigeration content in the desublimation system is recycled within a CO_2 recovery plant and retained to a significant degree. Most preferably, contemplated plants operate with a plurality of desublimators that are fluidly coupled via valves and a control unit such as to allow each desublimator to operate in one of the following modes: a desublimation mode, a regeneration mode, a pre-cooling mode, and a deep-cooling mode.

In one preferred aspect of the inventive subject matter, a flue gas treatment plant includes a flue gas conditioning unit that cools flue gas in one or more heat exchangers, preferably using a cool CO_2 depleted flue gas to so produce a precooled flue gas at a low flue gas pressure. Contemplated plants further include a desublimation unit having multiple desublimators that are fluidly coupled to each other and the flue gas conditioning unit such that: (a) one desublimator receives the precooled flue gas from the flue gas conditioning unit and produces a cold CO_2-lean flue gas while solid CO_2 deposit in the desublimator; (b) another desublimator receives and is pre-cooled by the cold CO_2-lean flue gas and so forms the cool CO_2 depleted flue gas; (c) a further desublimator receives a warm liquid CO_2 stream at relatively high regeneration pressure to produce an effluent stream that includes at least some of the desublimated CO_2 (preferably in slurry form); and (d) yet another desublimator deep-cooled by a refrigeration cycle to a temperature at which CO_2 desublimates; and wherein the refrigeration cycle is thermally coupled to the effluent stream such that refrigeration content of the effluent stream cools a refrigerant in the refrigeration cycle.

It is further typically preferred that the flue gas conditioning unit also includes a second heat exchanger that cools the flue gas with residual refrigeration content of the cool CO_2 depleted flue gas leaving the first heat exchanger. Where desired or needed, the flue gas conditioning unit may further comprise a dehydration unit that removes water from the flue gas. Particularly suitable refrigeration cycles are closed refrigeration cycles, or semi-open cycle refrigeration cycles that use a portion of the cool CO_2 depleted flue gas as a refrigerant. Regardless of the nature of the cycle, it is also preferred that the refrigeration cycle includes a cross-heat exchanger that further cools the pressurized cooled refrigerant using refrigerant leaving the desublimator that is in deep-cooling mode.

Most typically, one or more of the desublimators contains structured packing, random packing, or a non-porous high surface area material. Additionally, it is preferred that the flue gas pressure is between 10 and 50 psia while the regeneration pressure is between 100-300 psia. Particularly preferred flue gas treatment plants will include a control system and a series of valves that are fluidly coupled to the plurality of desublimators to allow switching of an operational mode of at least one of the desublimators from a desublimation mode, a regeneration mode, a pre-cooling mode, or a deep-cooling mode to another one of the desublimation mode, the regeneration mode, the pre-cooling mode, and the deep-cooling mode.

Therefore, and viewed from a different perspective, the inventors also contemplate a method of treating flue gas in a flue gas treatment plant that includes a step of using a first desublimator to receive a precooled flue gas, and to produce solid CO_2 and a cold CO_2-lean flue gas (**107**) using desublimation. In another step, the cold CO_2-lean flue gas (**107**) is used to pre-cool a second desublimator to a temperature above desublimation temperature for CO_2, thereby forming a cool CO_2-depleted flue gas (**108**), and in yet another step, residual refrigeration content of the cool CO_2-depleted flue gas is used to cool a feed gas (**101**) to thereby form the precooled flue gas (**106**), wherein the first desublimator is deep-cooled using a refrigerant of a refrigeration cycle before the step of using the first desublimator, and wherein the refrigeration cycle is thermally coupled to a heat exchanger that cools the refrigerant in the refrigeration cycle using refrigeration content of stream within the flue gas treatment plant.

In especially preferred methods, the stream within the flue gas treatment plant is an effluent of a third desublimator, and most preferably, the effluent is a two-phase stream comprising liquid CO_2 and solid CO_2. It is still further preferred that solid CO_2 is removed from the first desublimator using a liquid CO_2 stream at a pressure and temperature (e.g., 100-300 psia; −10 to 40° C.) that does not allow for formation of gaseous CO_2. While not limiting to the inventive subject matter, the first desublimator is operated in at least some embodiments at a pressure of between 10-50 psia, and the flue gas and a stack gas leaving the flue gas treatment plant have a temperature of between 10-40° C.

Therefore, the inventors also contemplate a method of recycling refrigeration content in a desublimation flue gas treatment plant in which flue gas and a second desublimator are pre-cooled using refrigeration content of a cold CO_2-lean flue gas that leaves a desublimator to which the precooled feed gas (**106**) is fed. In another step, and before the first desublimator is operated in desublimation mode, the first desublimator is deep-cooled using a refrigerant of a refrigeration cycle, wherein the refrigerant is cooled by another desublimator effluent in the flue gas treatment plant (and most preferably an effluent of a desublimator in regeneration mode).

In especially preferred methods, the flue gas is pre-cooled in two separate heat exchangers, with the first heat exchanger cooling the feed gas to a temperature above 0° C., and the second heat exchanger cooling the feed gas to a temperature above a desublimation temperature for CO_2. Where desired or needed, the flue gas may be subjected to a dehydration step.

Various objects, features, aspects and advantages of the present invention will become more apparent from the following detailed description of preferred embodiments of the invention.

BRIEF DESCRIPTION OF THE DRAWING

FIGS. **1**A & **1**B show one exemplary configuration of CO2 removal from a flue gas with integrated cold recovery.

FIGS. **2**A & **2**B show the exemplary configuration of FIGS. **1**A & **1**B with flue gas compression/expansion.

DETAILED DESCRIPTION

The inventive subject matter is directed to various systems and methods for CO_2 removal from flue gas using desublimation that are particularly effective in the recovery of refrigeration content from streams within the system.

In general, contemplated systems and methods allow for CO_2 separation from flue gas as a result of differences in intrinsic thermodynamic properties between CO_2 and other components in the flue gas. More specifically, the inventors have developed systems and methods to capture solid CO_2 through desublimation at relatively low pressure, and recovery of the solid CO_2 via use of liquid CO_2 at relatively high pressure.

As the process of CO_2 desublimation is energy demanding, the inventors have developed systems and methods to recycle refrigeration content that allows substantially more economical operation. In one particularly preferred aspect, thermal integration between the flue gas entering the desublimators and the CO_2-lean effluent gas, and thermal integration between a deep cooling refrigeration cycle and a liquid CO_2 recovery stream provide substantial advantages as compared to heretofore known cryogenic processes. As a result, most or all of the input and output streams can be at about ambient temperature (e.g., 20° C.,±10° C.) as a large fraction of the refrigeration is recycled within the system.

In particularly preferred aspects of the inventive subject matter, desublimation of CO_2 is performed using a plurality of desublimation columns that are operated such that continuous pre-cooling, deep-cooling, desublimation, and/or regeneration for respective desublimation columns can be performed. As used herein, the terms "desublimation column" and "desublimator" are used interchangeably and denote the same device. Most typically, but not necessarily, systems and methods contemplated herein include at least four columns and associated piping such that one column can be operated as desublimator while the other columns can be subjected to pre-cooling, deep-cooling, and regeneration, respectively. It is moreover generally preferred that the systems and methods provided herein employ flue gas conditioning to remove water and reduce the temperature of the flue gas prior to entry of the cooled flue gas into the desublimator. As will be explained in more detail below, flue gas conditioning as well as pre-cooling is advantageously performed using residual refrigeration content of the flue gas exiting the desublimation column. To even further economize operation, refrigeration content of desublimated CO_2 is used to cool (partially or even entirely condense) a refrigerant of a preferably closed refrigeration cycle that is configured to deep-cool a desublimation column in preparation for desublimation.

With respect to flue gas conditioning it is generally preferred that the flue gas is boosted or pressurized and cooled prior to entering a desublimator, preferably using a booster/blower or a compressor. Most advantageously, cooling of the flue gas is accomplished via heat exchange with CO_2-lean flue gas produced by a desublimator (or a pre-cooling desublimator) and/or an external refrigerant. Optionally, refrigeration content may be derived from expansion of CO_2-lean flue gas as also further detailed below. Most typically, a dryer may be used to remove at least a portion (and preferably substantially all) of the water content (and other condensable components) from the flue gas. However, it should be noted that in a further aspect of the inventive subject matter, the flue gas is not completely dried before it enters the desublimator. In this case, it is preferred that water from the flue gas is mostly removed by cooling the flue gas below the dew point, followed by removal of the water in a subsequent knock-out drum. The water that remains in the flue gas will then desublimate in the CO_2 desublimator. The solid water is then melted by the warm CO_2 liquid, is entrained in the desublimator effluent stream, and can be recovered, for example, by a liquid dryer.

It should further be noted that the flue gas refrigeration will preferably be performed in multiple stages, with a first stage cooling the flue gas to a temperature above the freezing point of water (i.e., above 0° C.), which advantageously allows condensation of most of the water contained in the flue gas. A second stage can then be used to chill the dehydrated feed gas to a temperature below the freezing point of water but above the desublimation point of CO_2 (i.e., below 0° C. and above −100° C., more typically above −115° C. at about atmospheric pressure). Residual water content can be removed in various manners, including molecular sieves or glycol driers. Still further, it should be recognized that flue gas cooling is most preferably performed using refrigeration content from within the CO_2 desublimation system. Thus, suitable sources of refrigeration content include the CO_2-lean flue gas, refrigerant of the closed cycle refrigeration loop for deep-cooling, and CO_2 liquid for regeneration, preferably where the liquid is a two-phase liquid.

Most typically, the flue gas is a combustion gas of combustor of a turbine in a power production plant, but may also be a combustion gas from one or more boilers, heaters, or even exhaust gas from an incinerator or catalyst regenerator. Thus, the nature of suitable flue gases may vary considerably. However, it is generally preferred that the flue gas is produced in relatively significant quantities, for example, at a rate of at least 10 scfm, more typically at least 1,000 scfm, and most typically at least 10,000-100,000 scfm, and even higher. Based on the nature of the flue gas and prior treatment (e.g., desulfurization, NO_x removal, particulate removal, etc.), chemical composition and temperature of the flue gas vary considerably. Thus, in most aspects of the inventive subject matter, the flue gas is pre-treated to remove one or more undesirable components (e.g., SO_x, NO_x, Hg, ash, other particulates, etc). In yet further contemplated aspects, it is preferred that the flue gas will have a temperature of less than 200° C., more preferably less than 100° C., even more preferably less than 50° C., and most preferably less than 30° C. Especially preferred flue gas temperatures will thus be in the range of between 10-50° C., 20-70° C., 30-80° C., or 15-90° C.

Suitable CO_2 levels in the flue gas may also vary. However, it is generally preferred that the CO_2 concentration in the flue gas is between 0.1-2.0 vol %, between 2.0-5.0 vol %, between 5.0-20 vol %, and less typically between 20-50 vol %. Most typically, the CO_2 concentration in the flue gas is between 5-20 vol %, or between 10-25 vol %. It should still further be appreciated that where the flue gas was not subject to pretreatment, such pretreatment may be performed in a separate desublimator. For example, SO_x or NO_x removal may be carried out by desublimation of SO_x or NOx components prior to desublimation of CO_2.

Where the flue gas is provided by a flue gas source that is sensitive to back pressure (e.g., turbine combustor), it is generally preferred that the flue gas is boosted to a pressure that is at least the back-pressure of the downstream components (e.g., desublimation columns and heat exchangers), typically between 15-30 psia, more typically between 30-50 psia, and in some cases between 50-150 psia. Where desublimation is performed at elevated pressures, the flue gas may be compressed to such pressures, typically between 25 and 125 psia, as described in more detail below.

It should be appreciated that desublimation is a process of transforming gaseous CO_2 into solid CO_2 without undergoing a liquid phase transformation. Desublimation is achieved in most typical cases using low pressure and temperature conditions, and the person of ordinary skill in the art will readily be apprised of suitable desublimation conditions with reference to phase diagrams well known in the art (e.g., 2D or 3D phase diagrams, temperature/entropy diagram, pressure enthalpy diagram, etc.). For example, desublimation temperatures for CO_2 quantities typically encountered in flue gases will generally be below −90° C., more typically below −100° C., even more typically below −115° C., and most typically below −130° C. where the flue gas pressure is between 15-30 psia. At elevated pressures, the desublimation temperature will rise as can be readily taken from known phase diagrams.

With respect to desublimation devices it is generally contemplated that at least one, but more typically more than one desublimators are used to capture the CO_2 from the flue gas and recover the CO_2 as solid CO_2. It is still further particularly preferred that the desublimators contain a structured packing to more effectively desublimate CO_2 and/or to allow for facile regeneration using liquid CO_2. However, numerous alternative packing materials that increase the surface area are also contemplated herein, and especially non-porous random packing materials. Porous packing materials are generally less preferred and in most instances even excluded.

Notably, and with further reference to known phase diagrams, CO_2 will only desublimate (and not liquefy) at sufficiently low temperatures and low partial pressure, while solid CO_2 can be recovered at a later point as liquid CO_2 (or as a solid/liquid slurry) at higher pressures and temperatures without generating gaseous CO_2. In one especially preferred manner of operation, multiple desublimators are operated in a coordinated cycle in which one desublimator is used for desublimation, another for pre-cooling, a further for recovery of the solid CO_2, and yet another one for deep-cooling. Seamless operation of the desublimators may be achieved by use of valves and suitably configured control circuits, wherein the valves open and close with respect to the function of the desublimator (i.e., whether the desublimator is desublimating, deep-cooling, recovering CO_2, or pre-cooling).

Furthermore, although the steps in the systems and methods are discussed in a particular order, various alternative sequences and numbers of desublimators are also deemed suitable. For example, it is contemplated that the exit stream of the desublimator which is desublimating the CO_2 from the flue gas enters the deep-cooling desublimator so that more CO_2 is extracted, or that two separate desublimators are performing the same function of CO_2 removal. Likewise, pre-cooling and/or regeneration may be performed on more than one desublimator at a time. Most typically, desublimation is ended in a particular desublimator upon recovery of a predetermined quantity of desublimated CO_2, or upon consumption of available cooling necessary for the desublimation of CO_2.

Due to the relatively high refrigeration demand for desublimation, it is preferred that the desublimator is cooled in a sequence of steps that include at least one pre-cooling step in which residual refrigeration content from cold CO_2-lean flue gas is used as a pre-cooling medium. However, it is contemplated that other process streams may also be used, either in direct contact, or via a heat exchanger and/or heat exchange fluid. Thus, external refrigeration is also deemed suitable to pre-cool the desublimator. Such external cooling may be particularly advantageous where the flue gas is produced from a gas combustion turbine, and where the gas is derived from LNG. For example, regasification of the LNG may be at least in part performed by using the refrigeration content of LNG to pre-/deep-cool the desublimation column, and the so heated LNG may be further warmed prior to combustion (which then produces the CO_2 containing flue gas). Depending on the flow rate and temperature demands, it should be appreciated that the CO_2-lean flue (or other) gas exiting the pre-cooling desublimator may be further used to cool the flue gas in the flue gas conditioning unit before it enters the desublimator. In addition, the CO_2-lean flue (or other) gas may be used to cool any other stream in the process until it has reached approximately ambient temperature (typically 20° C.,+/−10° C.). Using the CO_2-lean flue gas to cool streams in the process is more energy efficient since the CO_2-lean flue gas is already at a cooler temperature. Therefore, the net result is a conservation of energy, which is highly desirable.

With respect to deep-cooling of a pre-cooled desublimation column, it should be noted that any refrigerant may be used to deep-cool the desublimator and its packing to a temperature suitable to capture CO_2 by desublimation. However, it is typically preferred that the refrigeration cycle for deep-cooling is a closed refrigeration cycle that is thermally integrated with the regeneration cycle, and especially with the effluent stream of a regenerating desublimator such that the refrigeration content is conserved within the system. For example, warm pressurized refrigerant of the refrigeration cycle may be cooled by heat exchange with a CO_2 slurry mixture from the bottom of a regenerating desublimator, and further cooled by the refrigeration content of a refrigerant stream exiting the desublimator as shown in more detail below. Therefore, it should be recognized that it is possible to substantially reduce the need for external energy in the deep-cooling refrigeration and CO_2 regeneration operations.

In regeneration, recovery of solid CO_2 is preferably achieved by use of liquid CO_2 at high pressure (e.g., between 50-250 psia, between 100-300 psia, or between 250-500 psia) and preferably about ambient temperature (e.g., between 5° C. and 40° C.). However, it is noted that lower temperatures are also deemed suitable. Using liquid CO2 at such pressure and temperature, a portion of the deposited, solid CO_2 from desublimation is transformed into a liquid phase CO_2 (and in most cases not to gaseous CO_2). It should be appreciated that once the desublimator has achieved the requisite high pressure to transform a portion of the solid CO_2 into liquid CO_2, the liquid CO_2 stream can be continuously pumped into the desublimator to recover additional solid CO_2. Thus, particularly preferred operating conditions for regeneration of the desublimator are conditions at which CO_2 can exist in the liquid and/or solid state but not in the gaseous state.

Therefore, it is generally preferred that the effluent stream of the desublimator during regeneration is a CO_2 slurry (i.e., a two-phase system comprising solid and liquid CO_2). Most preferably, the effluent stream may exchange heat with a portion of the deep-cooling refrigerant stream such that the effluent stream is heated to melt the slurry (i.e., to reduce or eliminate solid CO_2 from the slurry to thereby form a thinner slurry or single-phase CO_2 liquid) and such that the refrigeration content from the effluent stream remains within the system by recycling the refrigerant content to the deep-cooling operation. Additionally, one may also choose to heat the effluent stream using another (preferably waste heat) stream from the process in a heat exchanger or using an external energy source. Once enough liquid CO_2 is collected, one may choose to purge a portion out of the system by use of a pump to further processing, sale, or final disposition (e.g., sequestration).

FIGS. **1**A & **1**B show an exemplary process schematic according to the inventive subject matter. Here, flue gas **101** (typically desulfurized) enters a blower BL-**101** or other device to increase pressure of the flue gas. The flue gas typically has a relatively low concentration of CO_2, up to approximately 18 vol %. The blower generates a pressurized flue gas stream **102**, with a pressure high enough to overcome the pressure drop of the downstream system components to so avoid backpressure on the source of the flue gas.

Pressurized flue gas stream **102** enters first precooler E-**101** that is preferably configured as a heat exchanger in which refrigeration content of the cold, CO_2 depleted flue gas **109** is used to cool the pressurized flue gas stream **102**, thereby forming cooled pressurized flue gas stream **103**. Stream **103** is cooled and dried in dryer D-**101**, which may be a glycol or other suitable gas dryer. Water is removed from the cooled pressurized flue gas as stream **105**, forming dry cooled flue gas **104**, which enters a second precooler E-**102**. The second precooler E-**102** is preferably configured as a feed-effluent exchanger in which heat is transferred from the dry cooled flue gas **104** to the cool CO_2 depleted flue gas **108**. The so precooled dry flue gas **106** enters one of a series of desublimators (C-**101** A-D).

In FIGS. **1**A & **1**B, the precooled dry flue gas **106** enters the first desublimator (C-**101** A). However, it should be recognized that the precooled dry flue gas could enter any of the four desublimators, depending on the cycling service. Moreover, it should be noted that the flow path in the desublimator can be radial or axial, and that a suitable flow path will be readily determined by the skilled artisan. It is generally preferred that the desublimators are filled with a non-porous material, most preferably having a high surface area to so not significantly impede gas flow through the desublimator. Structured tower packing is especially preferable, but random packing may alternatively be used.

With further reference to FIGS. **1**A & **1**B, the packing is cooled to a temperature that is below the desublimation temperature of the CO_2 (typically at the pressure of the dry cooled flue gas or the precooled dry flue gas) before the start of the desublimation cycle. As the precooled dry flue gas **106** flows up through the packing, it is cooled as it exchanges heat with the packing. Solid CO_2 desublimates from the gas and collects on the packing media. The cold CO_2-lean flue gas **107** leaves the first desublimator C-**101** A, and is routed to a second desublimator C-**101** B. The cold CO_2-lean flue gas **107** cools the packing in the second desublimator C-**101** B and is thereby warmed by the packing media in the second desublimator. After a portion of the refrigeration content is recovered from the CO_2-lean flue gas, the gas exits the second desublimator as cool CO_2-depleted flue gas **108**. Remaining refrigeration content in the cool CO_2-depleted flue gas **108** cools the dry cooled feed gas **104** in exchanger E-**102**, to form CO_2-depleted gas **109** that further cools the pressurized flue gas in exchanger E-**101** before being vented to the atmosphere as stack gas **110**.

After the solid CO_2 has been deposited in the first desublimator C-**101** A, the solid CO_2 must be recovered. In FIGS. **1**A & **1**B, the recovery of previously desublimated CO_2 is performed in a third desublimator C-**101** C, which in an earlier cycle operated as desublimator. Here, a high pressure warm liquid CO_2 stream **201** enters the third desublimator and flows through the packing media. As the pressure in the CO_2 desublimator increases due to contact with the high-pressure warm liquid CO_2 stream **201**, the solid CO_2 in the third desublimator begins to melt. Effluent stream **202** (typically a two-phase stream comprising liquid and solid CO_2) is withdrawn from the third desublimator and is heated in the CO_2 liquid heater E-**104**, where the refrigeration content from the effluent stream **202** (CO_2 slurry) is recovered. As a result, a combined liquid CO_2 is formed and fed as stream **203** to liquid CO_2 collection drum V-**101**. Liquid withdrawn from the liquid CO_2 collection drum V-**101**, stream **204**, is split into streams **205** and **206**. Stream **206** enters the circulating liquid CO_2 pump P-**102**, while stream **205** enters the CO_2 product pump P-**101**. Stream **206** is pressurized and returned to the desublimator for additional CO_2 melting, as high-pressure warm liquid stream **201**. Stream **205** is pressurized and pumped to the CO_2 end-use destination (e.g., storage, sequestration, etc.), as stream **207**.

Before the CO_2 is desublimated on the packing media, but after the packing media has been cooled by the depleted flue gas, the packing is cooled below the desublimation temperature of CO_2 by a refrigerant. While numerous refrigerants are deemed suitable for use herein, it is especially preferred that the refrigerant comprises dry N_2, O_2, CO_2, air, CO_2 depleted flue gas, or any reasonable combination thereof. It should be noted that use of CO_2-depleted flue gas as the refrigerant is especially advantageous as that gas is already a dry gas (See FIGS. **2**A and **2**B, **307** and **308**).

Still referring to FIGS. **1**A & **1**B, cold refrigerant stream **301** enters a fourth desublimator C-**101** D for deep-cooling, which was previously subjected to pre-cooling with cold CO_2-lean flue gas. The cold refrigerant cools the packing material to decrease the temperature in the desublimator to allow for CO_2 desublimation in the next step of the cycle. In turn, the cold refrigerant warms as it pulls heat from the packing material and exits the desublimator as cool refrigerant stream **302**. In especially preferred aspects of the inventive subject matter, the remaining refrigeration content in the cool refrigerant **302** is used to cool (typically at least partially condense) chilled pressurized refrigerant **305** in exchanger E-**103**, thus forming warmed refrigerant stream **303**. The so formed warmed refrigerant stream **303** is routed to the refrigeration compressor K-**101** where its pressure is increased to yield warm pressurized refrigerant stream **304**. The warm pressurized refrigerant stream **304** is then fed to the liquid CO_2 heater E-**104** to thereby heat the effluent stream and form the chilled pressurized refrigerant **305**. As already noted above, the chilled pressurized refrigerant **305** is further cooled in E-**103** to form cold pressurized refrigerant stream **306** that is then expanded in the refrigerant expander T-**101** and work is produced. The so formed cold refrigerant stream **301** is routed back to the desublimator for deep cooling. Of course, it should be recognized that numerous alternative refrigeration systems may be used in conjunction with the teachings presented herein, and especially suitable systems are described in U.S. Pat. No. 5,483,806 to Miller et al., which is incorporated herein by reference.

Thus, it should be appreciated that the systems and methods of CO_2 desublimation of the inventive subject matter provide for heretofore unprecedented cold integration. In especially preferred aspects, residual refrigeration content of cold CO2-lean flue gas is used in a precooling step for a desublimator and flue gas cooling such that the temperature of the CO2-lean flue gas leaving the plant is no less than 0° C., more typically no less than 10° C., even more typically no less than 15° C., and most typically no less than 20° C. Additionally, it should be recognized that refrigeration content of previously desublimated CO_2 can be recovered by providing refrigeration duty in a closed refrigeration cycle that is used to deep-cool a desublimation column. Lastly, at least some of the refrigeration content from the closed refrigeration cycle can be recycled by heat exchange of the cool refrigerant stream against the chilled pressurized refrigerant.

Moreover, it should be appreciated that while desublimation is performed at about flue gas pressure, regeneration of the desublimation column is performed at substantially increased pressure to so allow for a phase transition of the solid CO_2 to liquid CO_2 (and most preferably at a pressure and temperature that allows only for liquid CO_2 and solid CO_2 but not gaseous CO_2 to exist).

FIGS. **2**A & **2**B depict a modification of the configuration of FIGS. **1**A & **1**B, in which desublimation process occurs at an elevated pressure, preferably 25-130 psia. With respect to the numerals in FIGS. **2**A & **2**B, the same considerations and modifications apply to like components which have like numerals. Here BL-**101** provides the elevated pressure (e.g., between 20-150 psia) to the flue gas and so increases the desublimation temperature, which in turn reduces work input required by the refrigeration cycle. Consequently, the total power needed per unit of CO_2 captured may be substantially reduced. In such systems and methods, it should be recognized that the energy used to reach the elevated pressure can be recovered using an expander after the CO_2-lean gas precools a desublimator (stream **108** into the expander). In such configuration, a portion of the CO_2-lean gas may be advantageously used as a refrigerant (via streams **307**, **308**).

It should be apparent to those skilled in the art that many more modifications besides those already described are possible without departing from the inventive concepts herein. The inventive subject matter, therefore, is not to be restricted except in the spirit of the appended claims. Moreover, in interpreting both the specification and the claims, all terms should be interpreted in the broadest possible manner consistent with the context. In particular, the terms "comprises" and "comprising" should be interpreted as referring to elements, components, or steps in a non-exclusive manner, indicating that the referenced elements, components, or steps may be present, or utilized, or combined with other elements, components, or steps that are not expressly referenced. Where the specification claims refer to at least one of something selected from the group consisting of A, B, C . . . and N, the text should be interpreted as requiring only one element from the group, not A plus N, or B plus N, etc.

What is claimed is:

1. A flue gas treatment plant, comprising:

a flue gas conditioning unit configured to cool a flue gas (**101**) in a heat exchanger using a cool CO_2 depleted flue gas (**108**) to thereby produce a precooled flue gas (**106**) at a flue gas pressure;

a desublimation unit comprising a plurality of desublimators that are fluidly coupled to each other and the flue gas conditioning unit such that:

(i) a first of the desublimators is configured to receive the precooled flue gas (**106**) from the flue gas conditioning unit and to produce a cold CO_2-lean flue gas (**107**) and solid CO_2;

(ii) a second of the desublimators is configured to receive the cold CO_2-lean flue gas (**107**) to thereby pre-cool the second of the desublimators, thereby forming the cool CO_2 depleted flue gas (**108**);

(iii) a third of the desublimators is configured to receive a liquid CO_2 stream (**201**) at a regeneration pressure and to produce an effluent stream (**202**);

(iv) a fourth of the desublimators is coupled to a refrigeration cycle that is configured to deep-cool the fourth of the desublimators to at least a temperature at which CO_2 desublimates; and

(v) wherein the refrigeration cycle is thermally coupled to the effluent stream (**202**) of the third of the desublimators such that refrigeration content of the effluent stream cools a refrigerant in the refrigeration cycle.

2. The plant of claim **1**, wherein the flue gas conditioning unit further comprises a second heat exchanger configured to cool the flue gas (**101**) using residual refrigeration content of the cool CO_2 depleted flue gas (**108**) leaving the heat exchanger.

3. The plant of claim **1**, wherein the flue gas conditioning unit further comprises a dehydrator that is configured to remove water from the flue gas.

4. The plant of claim **1**, wherein the refrigeration cycle is a closed refrigeration cycle.

5. The plant of claim **4**, wherein the refrigeration cycle uses a portion of the cool CO_2 depleted flue gas (**108**) as a refrigerant.

6. The plant of claim **1**, wherein the refrigeration cycle further includes a cross-heat exchanger that is configured to use refrigeration content of a stream leaving the fourth of the desublimators.

7. The plant of claim 1, wherein at least one of the plurality of desublimators comprises a structured packing, a random packing, or a non-porous high surface area material.

8. The plant of claim 1, wherein the flue gas pressure is between 10 and 50 psia and wherein the regeneration pressure is between 100-300 psia.

9. The plant of claim 1, further comprising a control system and a series of valves fluidly coupled to the plurality of desublimators and configured to allow switching of an operational mode of at least one of the desublimators from one of a desublimation mode, a regeneration mode, a pre-cooling mode, and a deep-cooling mode to another one of the desublimation mode, the regeneration mode, the pre-cooling mode, and the deep-cooling mode.

* * * * *